Towards eddy-permitting estimates of the global-ocean and sea-ice circulation

D. Menemenlis, C. Hill, A. Adcroft, J. Campin, B. Cheng, B. Ciotti, I. Fukumori, P. Heimbach, C. Henze, A. Koehl, T. Lee, D. Stammer, J. Taft, and J. Zhang

During the past five years, estimates of ocean circulation constrained by *in situ* and remotely sensed observations have become routinely available and are being applied to myriad scientific and operational problems [*Stammer et al.*, 2002]. Under the Global Ocean Data Assimilation Experiment (GODAE), several estimates have evolved, regional and global, for applications in climate research, seasonal forecasting, Navy operations, marine safety, fisheries, the offshore industry, coastal management, etc. We report on recent progress by one such effort, the consortium for Estimating the Circulation and Climate of the Ocean (ECCO), towards a next-generation synthesis that is truly global, that covers the full ocean depth, and that admits eddies.

ECCO is funded by the National Oceanographic Partnership Program (NOPP) and is a collaboration between the Massachusetts Institute of Technology (MIT), the Jet Propulsion Laboratory (JPL), and the Sripps Institution of Oceanography (SIO). A distinguishing feature of ECCO estimates is their physical consistency. Estimates are obtained by least-squares fit of the MIT general circulation model (MITgcm [*Marshall et al.*, 1997]) to the available observations; they satisfy the model's time-evolution equations; property budgets are closed and there are no discontinuities when new data are inserted; and the error covariance is propagated through the same physical model as the state vector, hence more fully utilizing the available data. Although this represents a huge technical challenge, physically-consistent, coarse-resolution estimates are already in production and freely available (http://www.ecco-group.org/). These estimates have proved useful for a large number of oceanographic and interdisciplinary studies on topics such as ocean circulation [*Fukumori et al.*, 2004], biogeochemical cycles [*McKinley et al.*, 2004], air-sea fluxes [*Stammer et al.*, 2004], and geodetic studies [*Dickey et al.*, 2002].

But existing estimates lack the ability to resolve certain processes that are important for accurately representing key climate system dynamics, for example, meso-scale eddies, flow over narrow sills, boundary currents, regions of deep convection, sea-ice, and the Arctic Ocean. Here we describe three recent advances that bring physically-consistent, eddy-permitting, decadal-time-scale estimates of the global-ocean and sea-ice circulation within reach: 1) the configuration of an efficient eddying model that achieves a throughput approaching ten years of model integration per day of computation, 2) the demonstration that initial conditions and surface forcing fields estimated at coarse resolution improve the solution of an eddying model, and 3) the development and deployment of a hierarchy of methods for assimilating observations in a mathematically rigorous way.

Cubed-Sphere Model Configuration on a Parallel Supercomputer

The computational demands of rigorous ocean state estimation are enormous. Depending on the method and on the approximations that are used, the computational cost of state estimation is several dozen to several thousand times more expensive than integrating a model without state estimation. This has limited the resolution of existing ECCO solutions to horizontal grid spacings of order 100 km. Existing solutions also exclude the Arctic Ocean and lack an interactive sea-ice model, which restricts the utilization of satellite data over polar regions. Therefore, a necessary condition for a next generation synthesis is an efficient truly global model and significant computational resources.

For this work, a novel cubed-sphere grid projection is employed (Fig. 1). This grid permits relatively even grid-spacing throughout the domain, preserves local orthogonality for efficient and accurate time stepping, and avoids polar singularities [*Adcroft et al.*, 2004]. The ocean model is coupled to a sea-ice model that computes ice thickness, ice concentration, and snow cover as per *Zhang et al.* [1998] and that simulates a viscous-plastic rheology using an efficient parallel implementation of the *Zhang and Hibler* [1997] solver. Inclusion of sea-ice provides for more realistic surface boundary conditions in polar regions and allows the system to be constrained by polar satellite observations. The sea-ice model also permits estimation of the time-evolving sea-ice thickness distribution.

The results of Fig. 1 were obtained on a 512-processor, shared-memory SGI Altix computer operated by the NASA Advanced Supercomputing group at the Ames Research Center (NAS/ARC). Twenty such systems have been clustered together as part of Project Columbia, for a combined peak capacity of 61 teraflops, 50% more capacity than Japan's Earth Simulator. The shared memory architecture of the SGI Altix, the supportive computational resource culture at NAS/ARC, and the advanced numerics and parallelization capabilities of the MITgcm allow the eddying cubed-sphere configuration to be integrated with a throughput approaching ten years of simulation per day of computation. At this throughput, a next-generation global ocean and sea-ice synthesis that admits eddies becomes feasible. Below we present some early progress toward this goal.

Coarse-Resolution Surface Flux Estimates

A first question that has been addressed is whether the existing, coarse-resolution estimates of initial and surface boundary conditions can be used to initialize the eddy-permitting estimation effort. For this purpose two 1992-2001 integrations were conducted using a near-global configuration with 1/4-degree horizontal grid spacing. The first integration is initialized from the World Ocean Database [*Conkright et al.*, 1999] and forced by surface fluxes (wind stress, heat, and freshwater) from the NCEP meteorological reanalysis [*Kistler et al.*, 2001]. Initial conditions and surface fluxes for the second integration are from the ECCO 1-degree, adjoint-method optimization [*Stammer et al.*, 2004]. In addition to the specified surface fluxes, both integrations include surface relaxation terms to observed sea-surface temperature and salinity. The NCEP and the ECCO 1/4-degree simulations were compared to a comprehensive suite of observations [*Menemenlis et al.*, 2005a]. The ECCO boundary conditions generally improve the time-mean and the variability of upper ocean temperature (Fig. 2) and salinity. ECCO forcing also improves the paths of the Gulf Stream and of the Kuroshio, and the strength of the Equatorial Undercurrent. In spite of differences in the representation of meso-scale eddies and of other physical processes, the above results indicate that boundary conditions estimated at coarse resolution can improve eddying simulations. Existing solutions can therefore be used to initialize the eddy-permitting estimation effort, discussed next.

Towards Eddy-Permitting Estimates

Coarse-resolution ECCO solutions were obtained using three rigorous estimation approaches: an adjoint-model method [*Stammer et al.*, 2003], an approximate smoother [*Fukumori*, 2002], and an approach based on the computation of model Green functions [*Menemenlis et al.*, 2005b]. There is some limited experience in applying adjoint methods to regional eddy-permitting models [*Gebbie*, 2004] and work is underway to extend adjoint methods to global coarse-resolution and to regional high-resolution models that include sea-ice. Work is also underway to develop an approximate smoother for an eddy-permitting configuration. While development of adjoint methods and approximate smoothers continues, preliminary estimates are being obtained using a Green function approach. The fast throughput of the cubed-sphere configuration allows numerous model Green functions (or perturbation experiments) to be computed for different initial conditions, surface forcing fields, and empirical model parameters. For example, Fig. 3 shows impact of increased ice albedo on Arctic sea-ice extent. Formally combining these perturbations in order to minimize a cost function generates state estimates that are both consistent with the underlying model physics as well as with the available observations. Progress towards a first, physically-consistent, eddy-permitting estimate of the global-ocean and sea-ice circulation is documented at http://ecco.jpl.nasa.gov/cube_sphere/.

Concluding Remarks

The focus of ocean state estimation during the past five years has been to demonstrate the feasibility and utility of physically-consistent, global, sustained estimates, with considerable success for upper ocean and for equatorial processes. But many pressing scientific questions, for example, quantifying and monitoring ocean sources and sinks in the global carbon cycle, understanding the recent evolution and variability of the polar oceans, and quantifying the time-evolving term balances within and between different components of the Earth system, require much improved accuracy in the estimation of water mass formation and transformation rates, eddy-mixed layer interactions, and high-latitude processes. The accurate monitoring of these processes in turn requires developing state estimation systems, of the sort we have described in this article, that can fully capitalize on continuing advances in computational and observational technologies.

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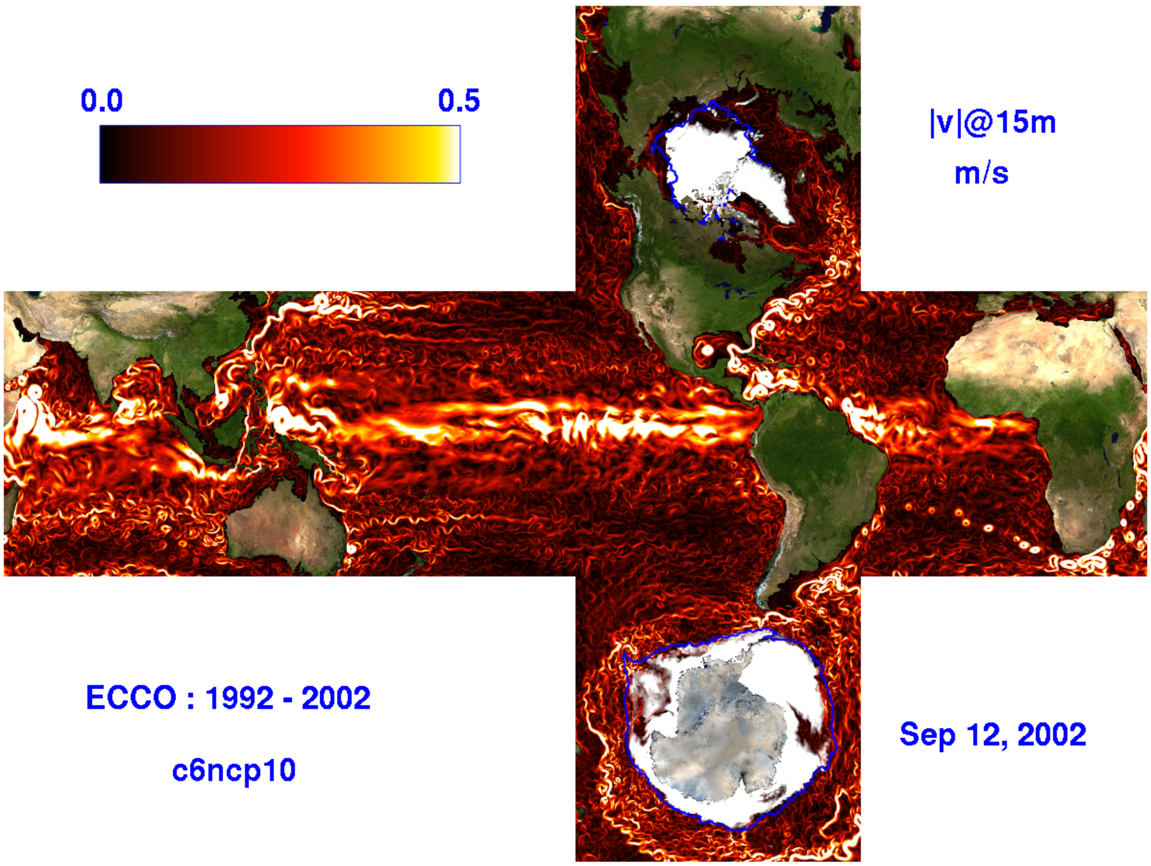

Figure 1: Cubed-sphere ocean model configuration. The figure shows simulated near-surface (15-m) ocean-current speed and sea-ice cover from a preliminary eddy-permitting integration. Units are m/s. Simulated sea-ice is shown as an opaque, white cover. The thin blue line is passive radiometer observations of sea-ice extent (15% concentration). Land masses and ice shelfs are overlain with NASA satellite imagery. Each face of the cube comprises 510 by 510 grid cells with mean horizontal spacing of 18 km. This model configuration can be integrated with a throughput approaching ten years of simulation per day of computation on a 512-processor partition of the Columbia Supercomputer. This fast throughput makes eddy-permitting estimates possible. Details and animations at http://ecco.jpl.nasa.gov/cube_sphere/.

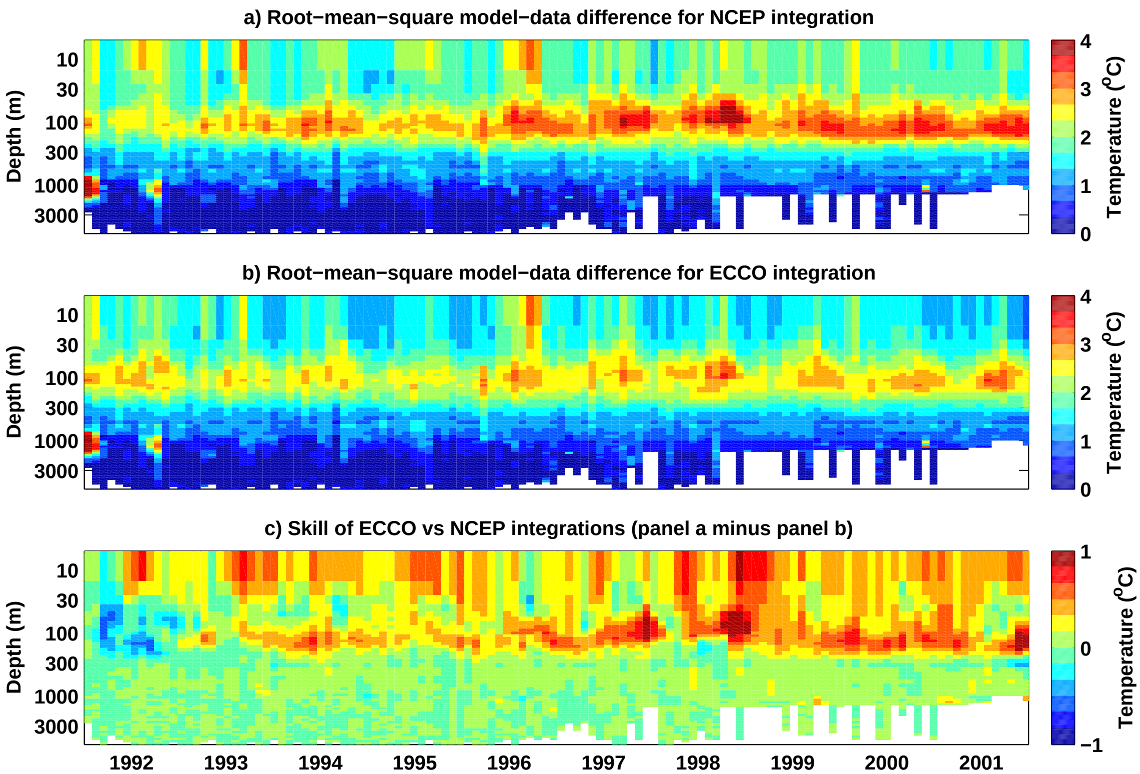

Figure 2: Globally averaged root-mean-square (rms) difference between simulated and observed temperature during 1992–2001. The top panel shows rms difference between observations and a 1/4-degree integration forced by NCEP-reanalysis surface fluxes. The middle panel shows rms difference between observations and an integration forced by ECCO fluxes. The bottom panel shows the difference between the first two panels. The preponderance of positive values in the bottom panel indicates that the ECCO-forced simulation is closer to observations than the NCEP-forced simulation. Existing coarse-resolution estimates can therefore be used to initialize the eddy-permitting estimation effort.

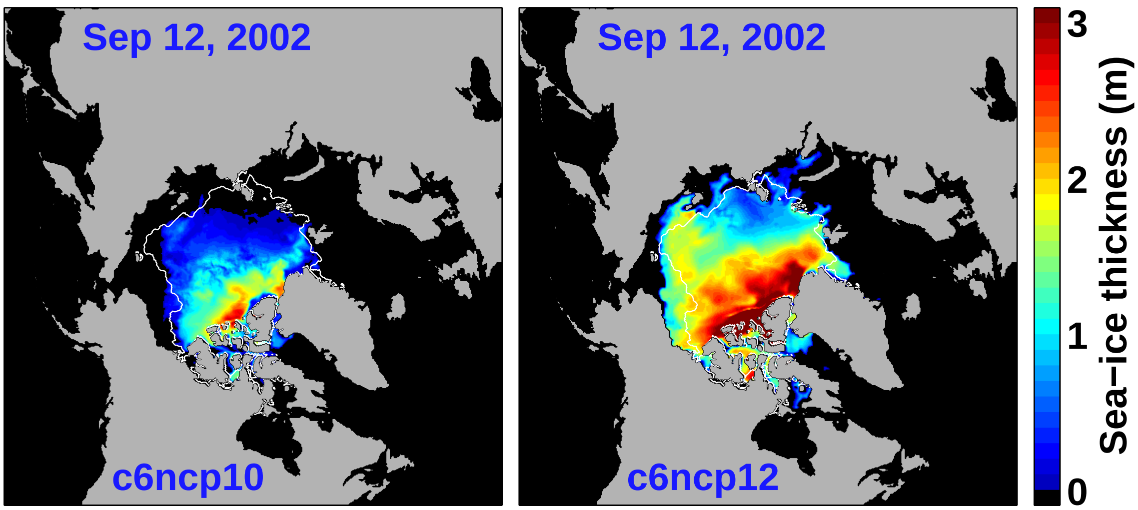

Figure 3: The fast throughput of the cubed-sphere configuration allows numerous model Green functions (or perturbation experiments) to be computed for different initial conditions, surface forcing fields, and empirical model parameters. The figure compares effective sea-ice thickness (thickness times concentration) of a baseline integration (left panel) to ice thickness from an integration with increased ice albedo (right panel). The thin white line is passive radiometer observations of sea-ice extent. Formally combining the different perturbations in order to minimize a cost function that measures overall difference between model and observations generates state estimates that are both consistent with the underlying model physics as well as with the available observations [*Menemenlis et al.*, 2005b].

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